NDCX-II capabilities for HIF-motivated experiments*

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11th Meeting of the HIFS-VNL Program Advisory Committee

LLNL, December 8 and 9, 2010

Heavy Ion Fusion Science Virtual National Laboratory

LLNL-PRES-463572

* This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, by LBNL under Contract DE-AC02-05CH11231, and by PPPL under Contract DE-AC02-76CH03073.

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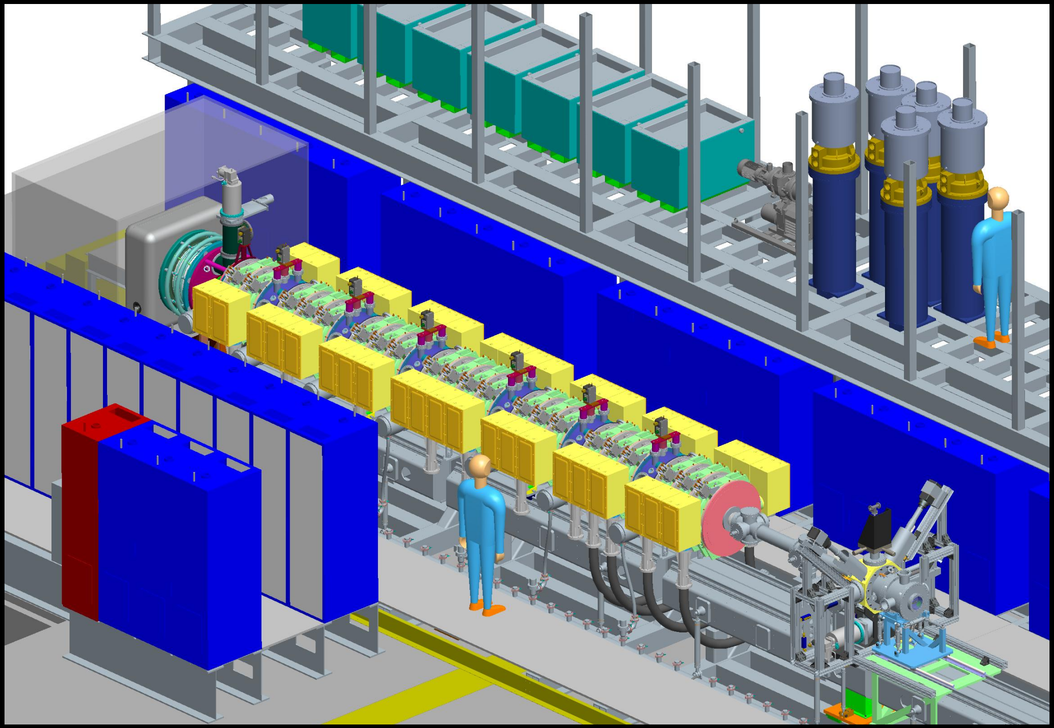
Neutralized Drift Compression Experiment-II (NDCX-II)

- A novel pulse-compressing ion induction accelerator
- A user facility for studies of:
  - HEDLP / warm dense matter physics
  - ion-driven target physics relevant to HIF
  - intense-beam physics relevant to HIF

Bieniosek talk

This talk



Outline

- Brief NDCX-II overview
- Experiments relevant to HIF driver
- Experiments relevant to HIF focusing
- Experiments relevant to HIF targets
- Upgrade potential

The drift compression concept is used twice in NDCX-II

Initial non-neutral pre-bunching for:

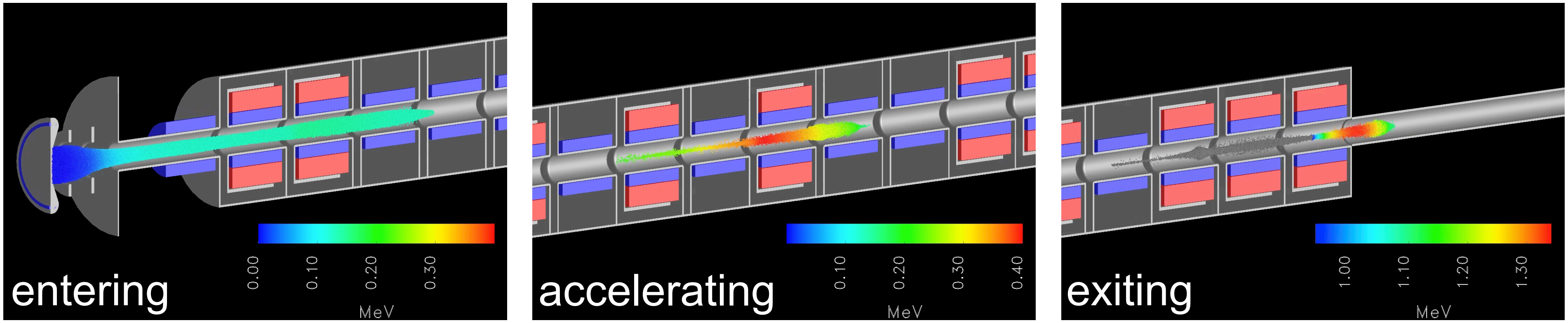
- better use of induction-core Volt-seconds
- early use of 70-ns 250-kV Blumlein power supplies from ATA

inject → apply tilt → drift → accelerate → apply tilt → neutral-ized drift → target

Final neutralized drift compression onto the target

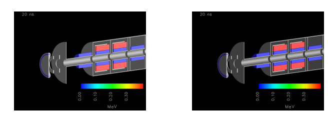
- Electrons in plasma move so as to cancel the beam's electric field
- Require $n_{plasma} > n_{beam}$ for this to work well
- Vacuum drift compression is also of interest

Simulations enabled development of the NDCX-II physics design



- New, fast 1-D (longitudinal) particle-in-cell code ASP enabled finding an attractive operating point within the large parameter space
- Injector, transverse beam confinement, and final focusing were developed using the Warp code in (r,z) geometry
- We used 3-D Warp calculations to assess performance in the presence of imperfections, set tolerances

These same tools will enable detailed comparisons of beam measurements and simulations, using “synthetic diagnostics”



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A. Friedman, *et al.*, *Phys. Plasmas* **17**, 056704 (2010).

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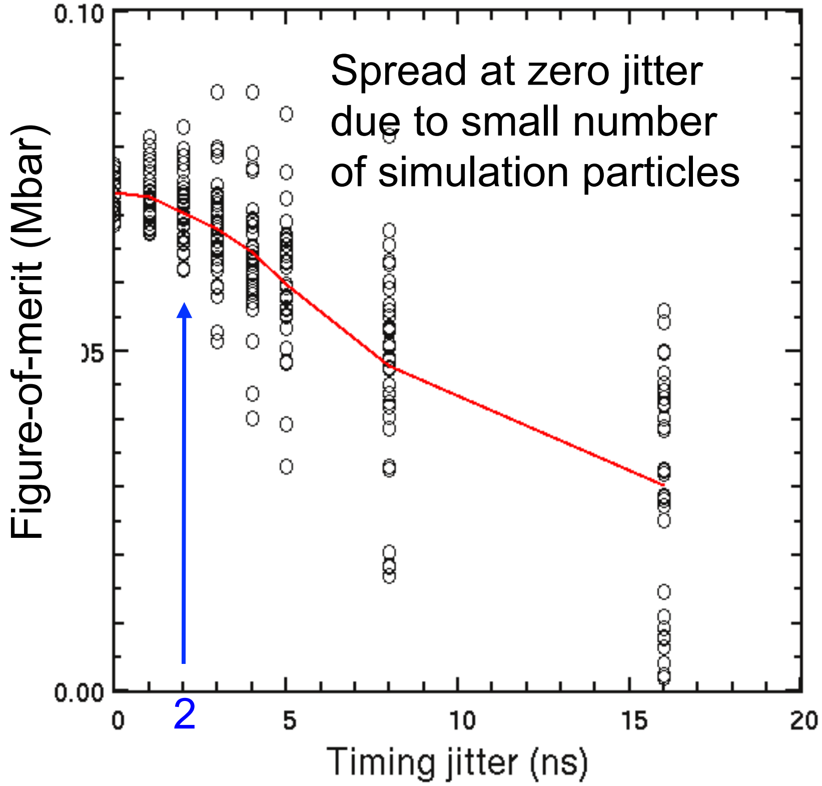
Ensembles of Warp runs indicate only minor degradation due to:

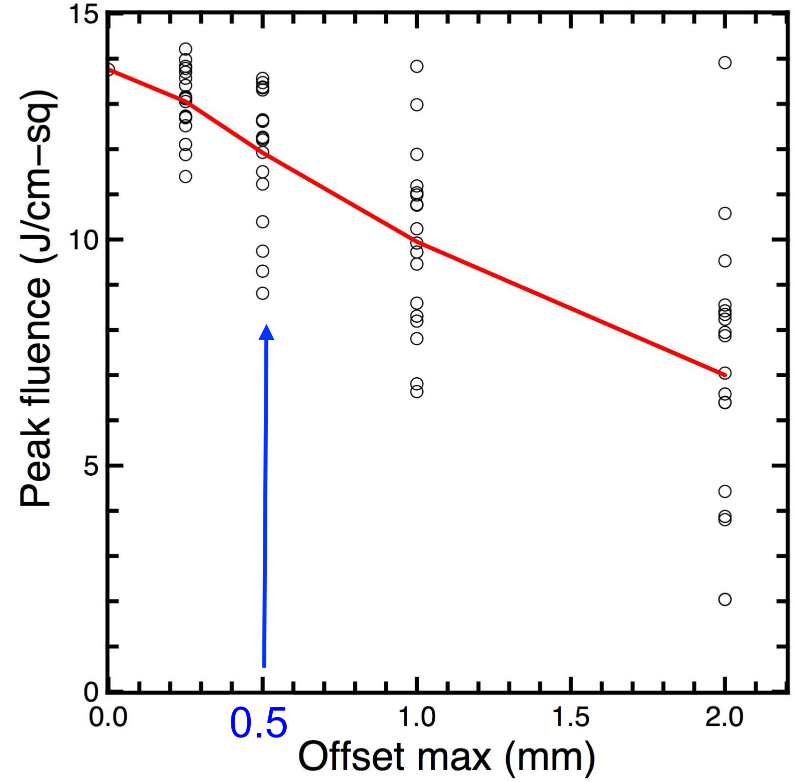
pulser timing jitter — magnet misalignment



- Random timing shifts were imposed on the accelerating voltage pulses.
- Nominal NDCX-II spark-gap jitter is 2 ns

This capability will be useful for studies of HIF drivers.

40g-12



- Random offsets were imparted to the solenoid ends.
- Nominal NDCX-II tolerance is 0.5 mm
- Beam “steering” via dipole magnets will center beam and minimize “corkscrew” distortion.

35g-15 (older 15-cell design)

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The NDCX-II accelerator and downstream line embody beam physics relevant to an HIF driver

- Collective beam dynamics:
  - Space-charge force is very large ("generalized perveance" up to 0.01)
  - Driver-like compression of non-neutral beam (in the NDCX-II accelerator)

    Space charge removes "tilt" as pulse compresses from ~500 to ~70 ns
  - Longitudinal waves are evident

- Non-ideal effects include:
  - Emittance growth (phase-space dilution) and "halo" formation
  - Beam - plasma interactions and instabilities
  - Aberrations in final focus
  - Stray "electron cloud" (could steer beam into pipe wall)

    All (or almost all) gaps run at ≥ 30 kV, while beam potential is ≤ 7 keV, so gap fields should sweep electrons from beam

These are among the first topics we'll study

NDCX-II experiments will address HIF driver questions

Driver-like drift compression

- non-neutral, in compression section of the accelerator (as mentioned above)
- non-neutral experiments in compression line (described below)
- neutralized

Beam head control

- NDCX-II beam resembles driver beam with most of flat-top removed
- Retuned pulsers could separately control head or tail of uncompressed beam

Aberrations in final focus

- Chromatic aberration correction schemes can be tested
- Beam tilt and strength of final-focus solenoid can be varied
- “Grote effect” (non-paraxial pulse stretching) can be assessed

Beam transport with and without tilt

- A magnetic-quadrupole section could be added
- A bend could be added

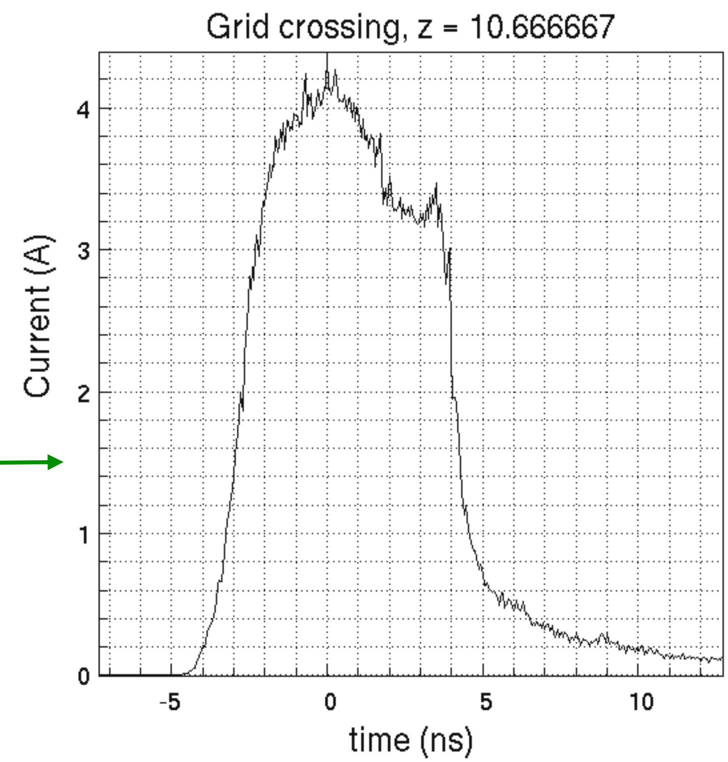
Beam diagnostics will be developed and tested

We can test non-neutral drift compression w/ NDCX-II output beam

- Removal of “tilt” for final focus in driver (minimize chromatic aberration); we’ll position a final-focusing optic at the stagnation point in NDCX-II
- As input to a Dielectric Wall Accelerator (need 5-10 ns; shorter is better)

- In Warp, *removed plasma* & *added extra transport solenoids* (Grote)
- Pulse duration is 4 x t_{RMS}, obtained from current-vs-time data at each z

	active cells	Final kinetic energy (MeV)	Peak current (A)	Min pulse duration (ns)
ndcx40g	12	1.2	3.	13.
ndcx40j	15	1.7	4.	8.
ndcx40h	18	2.4	8.	7.
ndcx39c	46	8.2	46.	2.



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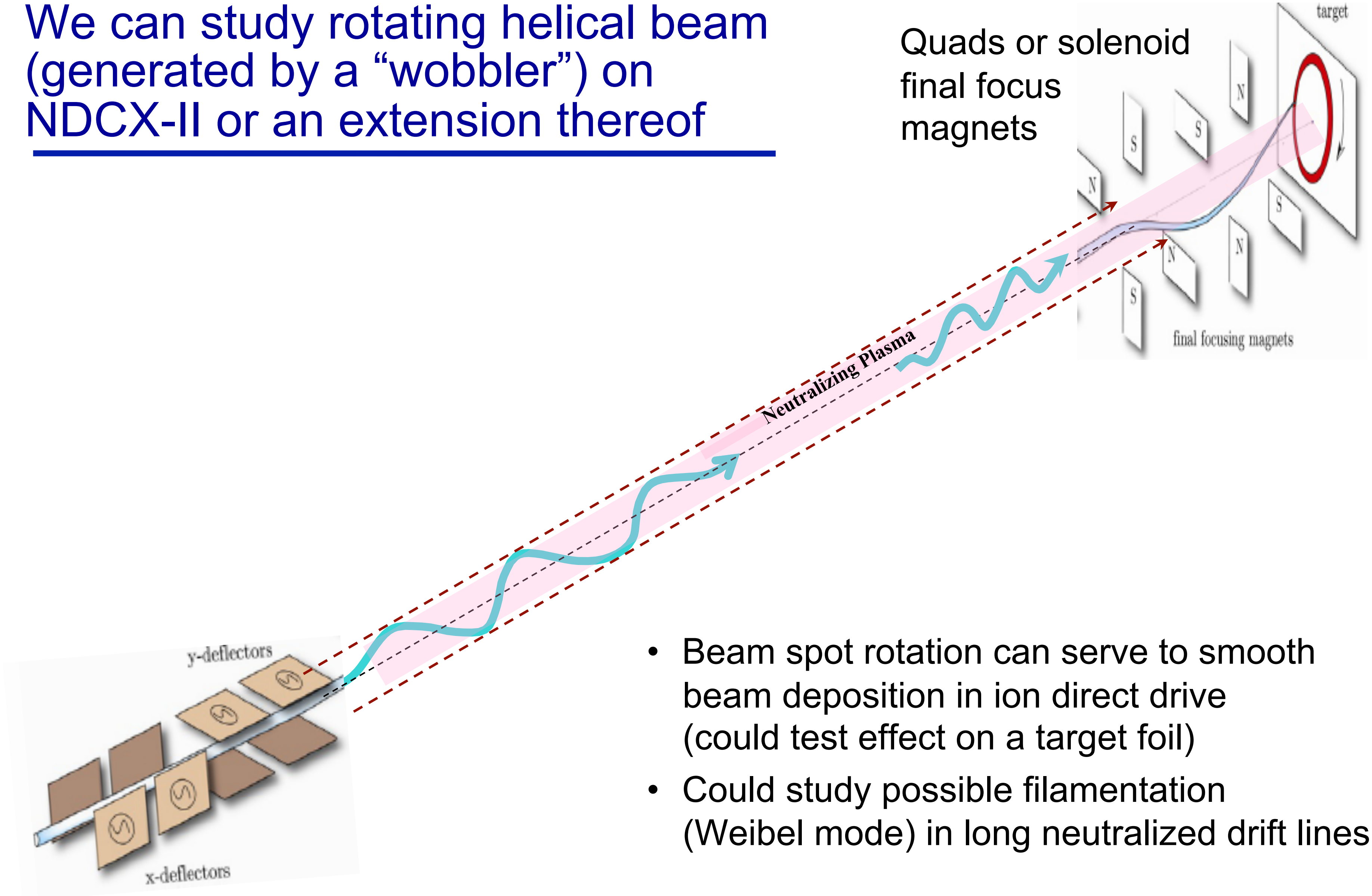
We can study rotating helical beam (generated by a “wobbler”) on NDCX-II or an extension thereof

Quads or solenoid final focus magnets

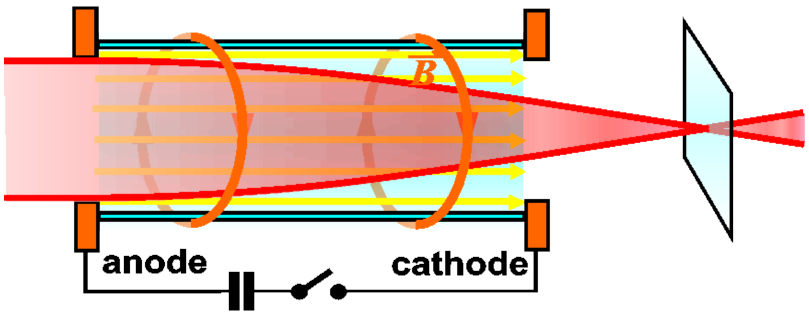


- Beam spot rotation can serve to smooth beam deposition in ion direct drive (could test effect on a target foil)
- Could study possible filamentation (Weibel mode) in long neutralized drift lines

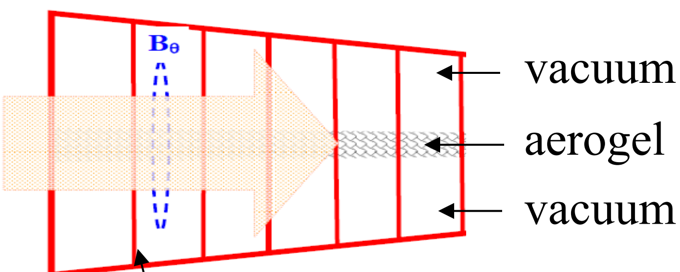
H. Qin, *et al.*, PRL 104, 254801 (2010); D. Welch, Proc. HIF ‘04

NDCX-II could be an effective platform for studying beam focusing systems beyond the 8 T Final Focus Solenoid

- B_θ lens: driven plasma lens

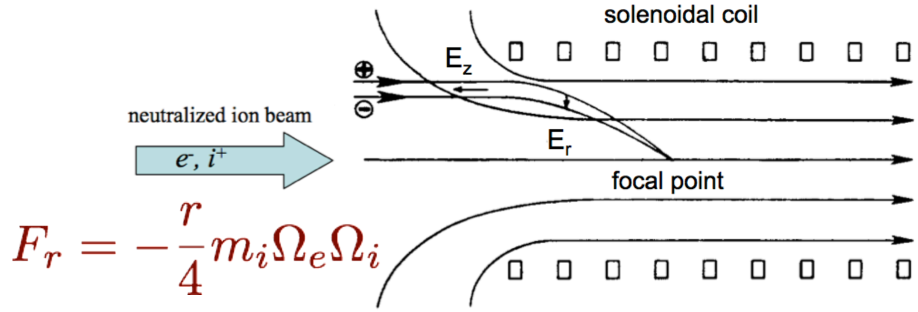


- B_θ lens: self-pinching via inhibition of electron return current (could test elements of this on NDCX-II)



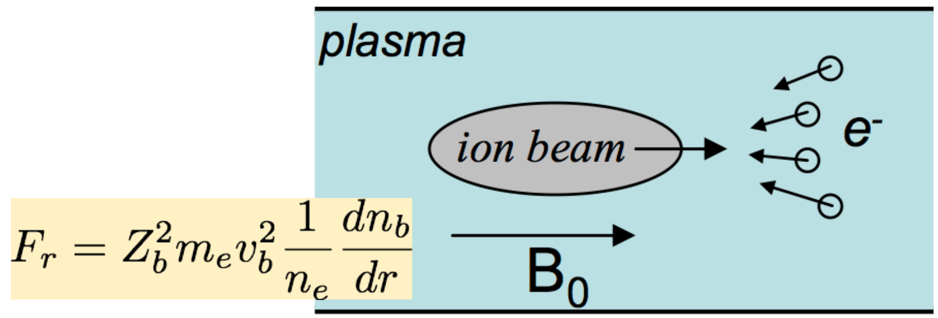
foils short out transverse E field; beam strips on first foil

- Robertson lens



$$F_r = -\frac{r}{4} m_i \Omega_e \Omega_i$$

- Electrostatic polarization focus



$$F_r = Z_b^2 m_e v_b^2 \frac{1}{n_e} \frac{dn_b}{dr}$$

M. Dorf, et al., PRL 103, 075003 (2009).

- Also:
  - Strong solenoids, perhaps 50 T
  - Quadrupole multiplets, including perhaps permanent-magnet quads

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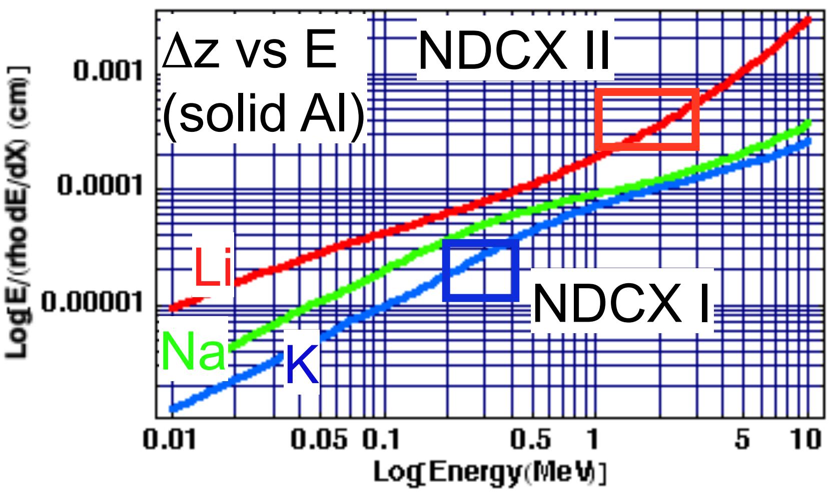
NDCX-II will enable study of ion beam energy coupling physics

Range increases with energy :



For NDCX-II we may use 10% Al foam:
Δz ≈ 20 μ (k.e. / 1 MeV)

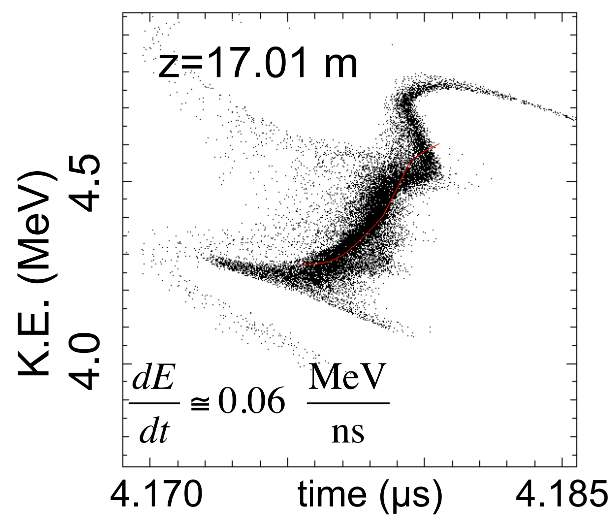
To "follow a shock", (where $v_{shock} \sim c_s$) the energy slew must be sufficiently rapid:

$$\frac{dE}{dt} \cong 0.10 \ \frac{\text{MeV}}{\text{ns}}$$

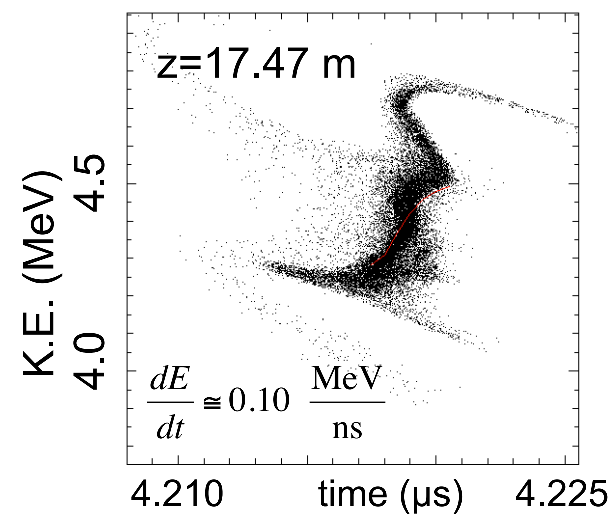
Placing foil upstream of best focus is a simple way to achieve energy ramp.

Using Warp, we looked at the energy slew rate, here on an extended NDCX-II.

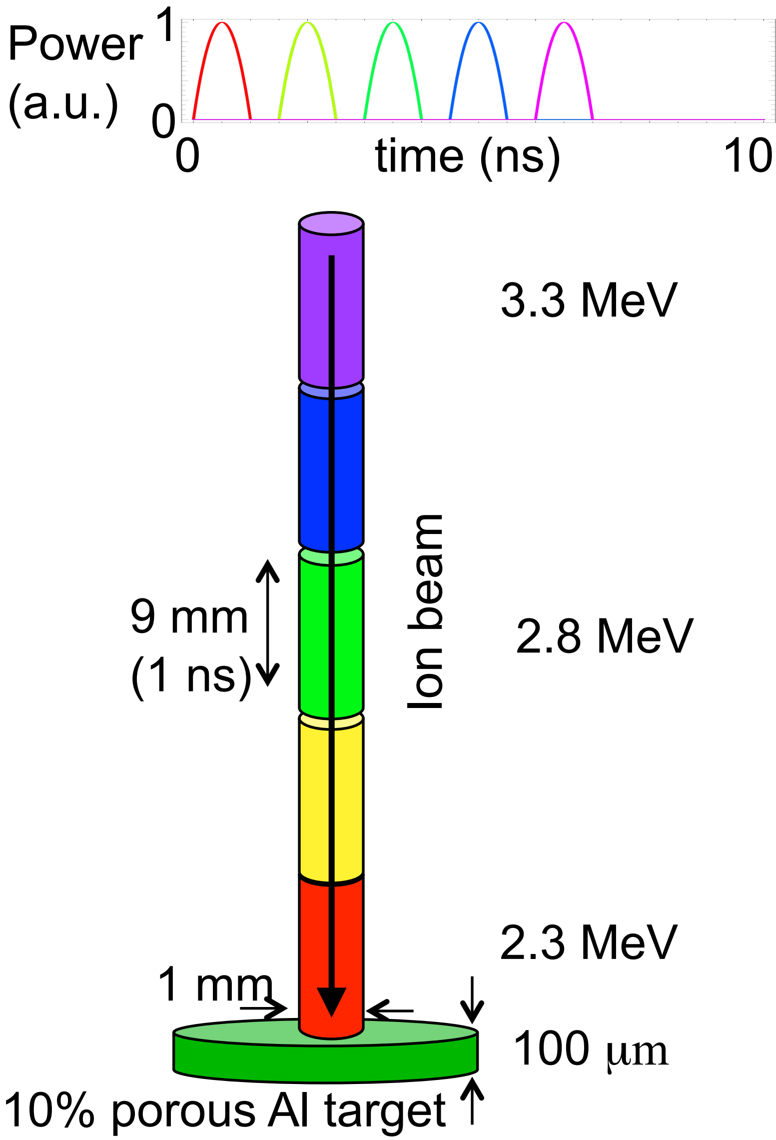
K.E. vs. time

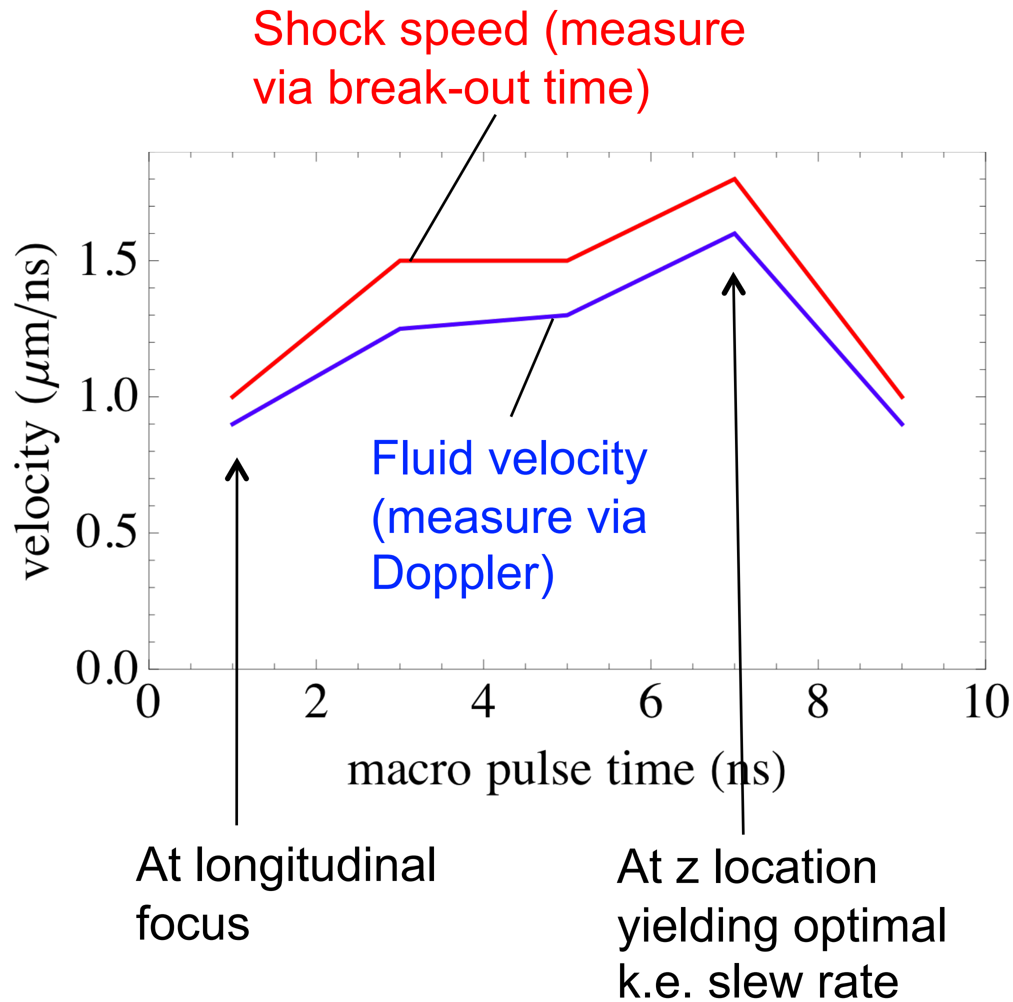


K.E. vs. time

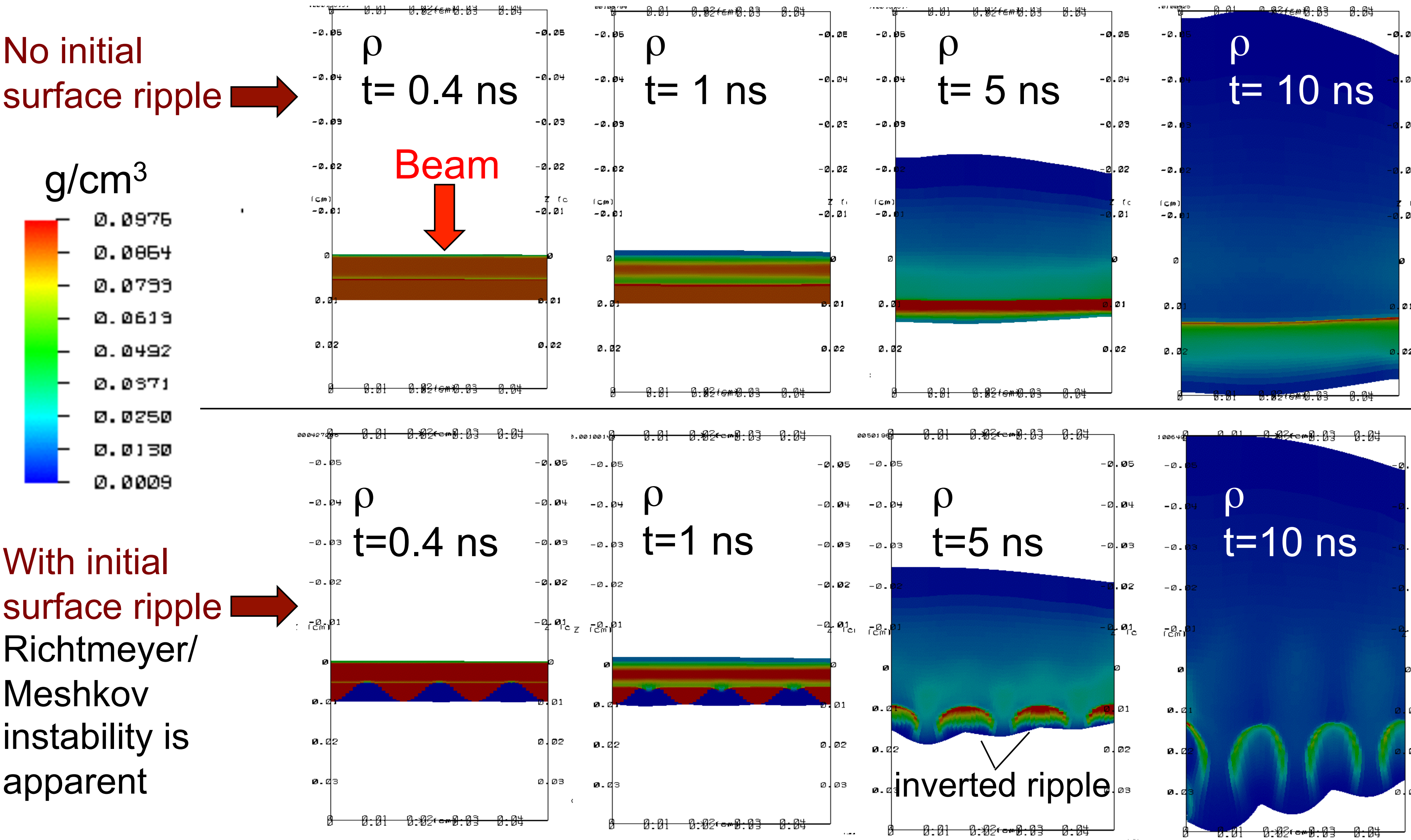


Hydra results quantify the effects of positioning target upstream of the plane of best longitudinal focus





HYDRA simulations using advanced NDCX-II/IBX parameters simulate possible hydrodynamic stability experiments particular to ions



23 MeV Ne, 0.1 μC, 1 ns pulse (advanced NDCX II / IBX) impinges on 100 μ thick solid H, T = 0.0012 eV, ρ = 0.088 g/cm^3

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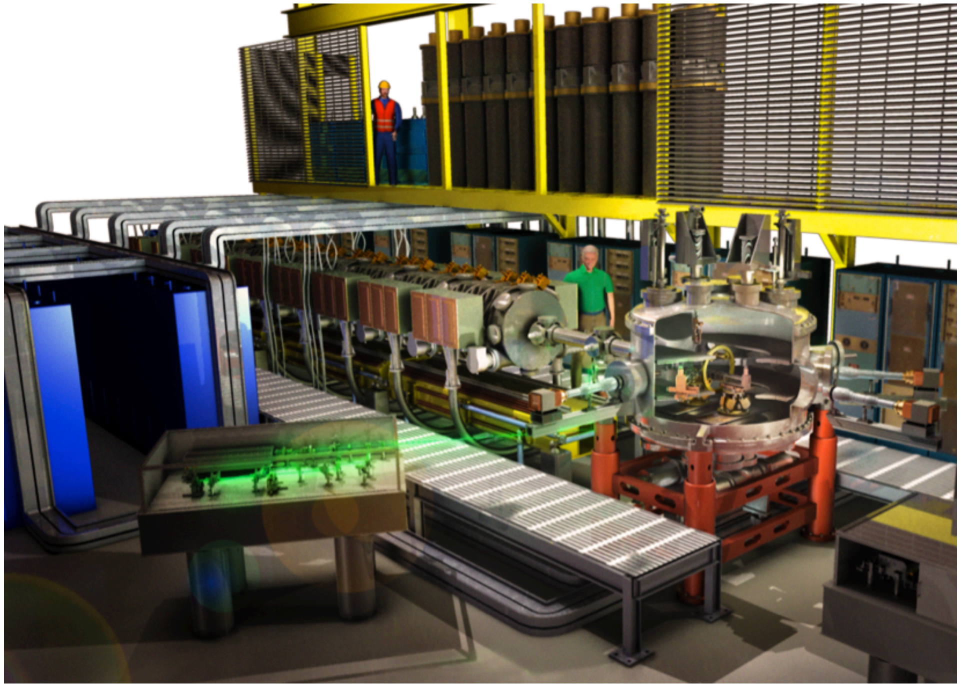
Considerably greater kinetic energies are possible within the existing framework

- NDCX-II is a modular system on rails, for flexibility and expandability.
- IB-HEDPX could be an extension of NDCX-II (if we want to use Li^+ ions)
  - we possess 50 ATA cells, sufficient for an upgrade to 8 MV or more
  - use of all cells requires an eastern extension of the B58 high bay
  - Cost would be ~$50 M: $20 M + $30 M user area (LCLS-HED-scale)



We'd like to be able to run with other ions or lower injected current

- For extended versions of NDCX-II and IB-HEDPX:
  - Pressure in a WDM target increases slowly as the k.e. of Li^+ ions is increased

    This is because the ion range increases with their k.e.

    Pressure increase for Li^+ comes mostly from shorter pulse and tighter focus
  - For HIF studies, *e.g.* energy ramps, an extended Li^+ machine would be useful
  - We need to work out the changes required to accelerate ions of atomic mass in the range of 12 (C^+) - 39 (K^+)
  - *Would benefit from a short-pulse laser-aided ion source*

- There are also near-term motivations:
  - Li^+ source has limited lifetime; might want to run tests at < 1 mA/cm^2
  - Might want to test w/ another ion, *e.g.*, K^+ (concern about contamination)
  - Might want to study, *e.g.*, corkscrew with a Li^+ "pencil" beam
  - The nominal longitudinal "bucket" would be mismatched – how much beam can we catch simply by adjusting gap firing times (& solenoids)?

NDCX-II performance for typical cases in 12-21 cell configurations

	NDCX-I (bunched beam)	NDCX-II			
		12-cell	15-cell	18-cell	21-cell
Ion species	K^+ (A=39)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)	Li^+ (A=7)
Charge	15 nC	50 nC total 25 2xFWHM	50 nC total 25 2xFWHM	50 nC total 25 2xFWHM	50 nC total 30 2xFWHM
Ion kinetic energy	**0.3 MeV**	**1.2 MeV**	**1.7 MeV**	**2.4 MeV**	**3.1 MeV**
Focal radius (50% of beam)	**2 mm**	**0.6 mm**	**0.6 mm**	**0.6 mm**	**0.7 mm**
Duration (bi-parabolic measure = $\sqrt{2}$ FWHM)	**2.8 ns**	**0.9 ns**	**0.4 ns**	**0.3 ns**	**0.4 ns**
Peak current	**3 A**	**36 A**	**73 A**	**93 A**	**86 A**
Peak fluence (time integrated)	0.03 J/cm^2	13 J/cm^2	19 J/cm^2	14 J/cm^2	22 J/cm^2
Fluence w/in 0.1 mm diameter, w/in duration		8 J/cm^2	11 J/cm^2	10 J/cm^2	17 J/cm^2
Max. central pressure in Al target		0.07 Mbar	0.18 Mbar	0.17 Mbar	0.23 Mbar
Max. central pressure in Au target		0.18 Mbar	0.48 Mbar	0.48 Mbar	0.64 Mbar

NDCX-II estimates are from (r,z) Warp runs (no misalignments), and assume uniform 1 mA/cm^2 emission, high-fidelity acceleration pulses and solenoid excitation, perfect neutralization in the drift line, and an 8-T final-focus solenoid; they also employ no fine energy correction (e.g., tuning the final tilt waveforms)

From P. Seidl: A balanced IFE research program includes:

Target physics & design

Direct and indirect drive targets for power plant and for an intermediate target and accelerator physics facility

Symmetry requirements, beam pointing

Stability

Accelerator physics & driver design:

Multi-beam ion sources, injection, matching

Focusing elements: magnetic, electric quads, solenoids

Halo formation and control

Acceleration

Neutralized & un-neutralized drift compression

Achromatic focusing systems

Time dependent chromatic correction

Final focusing, reactor interface, design

Reactor and driver interface

Tritium breeding

Radiation shielding

Liquid protection

Enabling technology

Pulsed power

Insulators (e.g.: glassy ceramics, embedded rings)

Superconducting materials (Nb3Sn)

Quadrupole, solenoid design

Focusing arrays

Reactor materials and components

- Items in red are explored (to varying degrees) on the baseline NDCX-II accelerator.
- Items in green could be explored via add-ons.